Machines-2794111.R1 entitled "Guiding the selection of multi-vector MPC techniques for multiphase drives"

Reply to reviewers

The authors would like to thank the reviewers and editors for their helpful comments. A list of the changes based on the reviewers' comments is included in what follows. Remarks of the reviewers are in italic and black ink, whereas the authors' reply is given in standard font and blue ink. The changes have been highlighted in the new version of the manuscript in blue ink.

Reviewer: 1

This paper has listed four control schemes based on multi-vector MPC, taking the three influencing factors of high current quality, appropriate current tracking and minimum energy loss as examples, and carried out experimental analysis under different working conditions. Finally, according to the experimental results, it analyzed that the appropriate control strategy was selected according to different test conditions, which is enough work and has certain innovation.

Thank you so much for your comments about our work.

However, there are the following problems, which I hope the author can improve:

1. It is suggested to add some relevant research status of scholars in the introduction to highlight the problems solved on the basis of previous research in this paper.

Thank you for your efforts to improve the quality of this work. Some recent research works have been added to the new manuscript version in order to update the description of the state of art of the field. In this manner, the proposed work aims to provide a more complete state of the art to future readers.

2.[A] and [B] are matrices that allow characterizing the dynamics of the described 6PH-IM. However, [A] and [B] are used repeatedly in the text, and it is recommended to write them in detail.

To clarify the understanding of the original manuscript, the authors have defined both $[A]$ and $[B]$ matrices in a new appendix section.

3. The author is advised to check the full text for punctuation, such as the absence of ", "after the Tm in line 199.

Sorry for the typo, this one has been solved. In addition, the manuscript has been revised in order to mitigate possible typos.

4. Data explanation can be appropriately added to the analysis of experimental results to be more convincing.

The new manuscript version has been modified to describe the existence of data that can be employed by the readers to obtain the provided results or even to carry out additional analysis.

Please see the Experimental validation sections where this information has been added.

Reviewer: 2

The article proposes an interesting comparison between different control strategies for six-phase motors based on Model Predictive Control (MPC). Although the article highlights various aspects to draw conclusions regarding the comparison among different MPC control strategies, many sections of the article are challenging to understand, and often, the descriptions are unclear. Some suggestions are listed below. Moreover, too many self-citations are present among the references.

Thank you so much for your significant efforts to enhance the quality of our work. Taking into account the reviewer comment, the number of self-citations has been reduced.

1) *Please, could you provide specific references related to the sentence in lines (43-44): "For example, the development of different overmodulation algorithms has allowed a higher dc-link voltage utilization of linear controllers and, consequently, a faster dynamic response".*

Thank you for your comment. Different references [R2.1-R2.4] have been added to the manuscript in order to simplify the location of works focused on the development of overmodulation techniques.

[R2.1] A. M. Hava, R. J. Kerkman and T. A. Lipo, "Carrier-based PWM-VSI overmodulation strategies: analysis, comparison, and design," *IEEE Transactions on Power Electronics*, vol. 13, no. 4, pp. 674-689, July 1998, doi: 10.1109/63.704136.

[R2.2] Ó. López et al., "Carrier-Based PWM Equivalent to Multilevel Multiphase Space Vector PWM Techniques," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 7, pp. 5220-5231, July 2020, doi: 10.1109/TIE.2019.2934029.

[R2.3] D. G. Holmes and T. A. Lipo, Pulse Width Modulation for Power Converters: Principles and Practice, Hoboken, NJ, *USA,Wiley*, 2003.

[R2.4] G. Carrasco and C. A. Silva, "Space vector PWM method for five-phase two-level VSI with minimum harmonic injection in the overmodulation region", *IEEE Transaction on Industrial Electronics*, vol. 60, no. 5, pp. 2042-2053, May 2013.

2) *Please, could you clarify the concept of a multi-vector solution? Are the advantages of a multi-vector solution possible because they are applied in multi-winding motor drives? Furthermore, are these advantages intrinsically obtained by utilizing multi-winding motor drives where a multi-vector solution is applied? Or is it possible to consider a multi-vector solution for three-phase motor drives?*

In general, a multi-vector solution involves the application of more than one voltage vector within the same sampling period. This solution is also applicable in three-phase electric drives [R2.5-R2.8]. Nevertheless, in multiphase systems, the mentioned multi-vector solutions are specially interesting since they allow reducing the current harmonics in the secondary plane. Please note that, in asymmetrical six-phase machines all active voltage vectors of the main plane are also mapped onto active voltage vectors in the secondary subspace (please see Figure 2 of the manuscript). Therefore, the application of a single switching state per control period does not permit an active production of torque/flux with a null injection of secondary currents.

[R2.5] L. Guo, M. Chen, Y. Li, P. Wang, N. Jin and J. Wu, "Hybrid Multi-Vector Modulated Model Predictive Control Strategy for Voltage Source Inverters Based on a New Visualization Analysis Method," *IEEE Transactions on Transportation Electrification*, vol. 9, no. 1, pp. 8-21, March 2023, doi: 10.1109/TTE.2022.3161583.

[R2.6] J. Sun, Y. Yang, R. Chen, X. Zhang, C. S. Lim and J. Rodriguez, "An efficient multi-vector based model predictive current control for PMSM drive," *CPSS Transactions on Power Electronics and Applications*, doi: 10.24295/CPSSTPEA.2023.00044.

[R2.7] Y. Yang et al., "Multiple-Voltage-Vector Model Predictive Control With Reduced Complexity for Multilevel Inverters," *IEEE Transactions on Transportation Electrification*, vol. 6, no. 1, pp. 105-117, March 2020, doi: 10.1109/TTE.2020.2973045

[R2.8] W. Deng, Q. Zhang and W. Xie, "An Enhanced Virtual Vector-Based Model Predictive Control for PMSM Drives to Reduce Common-Mode Voltage Considering Dead Time Effect," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 11, no. 5, pp. 4659-4668, Oct. 2023, doi: 10.1109/JESTPE.2023.3298666

3) *What does 'secondary components' mean in line (56)? Please provide clarification.*

As in the case of the three-phase systems, the vector space decomposition approach can be employed in the field of multiphase machines to express phase variables onto different orthonormal subspaces. Since the number of phases increases in multiphase systems, the number of available subspaces also augment. Concerning six-phase electric drives, after the application of Clarke matrix transformation phase variables are mapped onto three different orthonormal subspaces [51]. The plane related to torque/production is termed as α-β subspace or main plane, this one also appears in conventional three-phase systems. The secondary plane or x-y subspace only produces stator copper losses in distributed winding machines, and it is exclusive of multiphase machines. The term 'secondary components' refers to any voltage/current that is mapped onto this secondary x-y subspace after the Clarke transformation. Finally, the currents of the third subspace related to zero sequence components can be neglected because the machine is configured with two isolated neutral points and consequently, they cannot flow.

This notation has also been followed in other previous papers (e.g., [18]), but it has been clarified in the new version of the manuscript for the sake of clarity.

4) *What does 'secondary currents' mean in line (56)? Please provide clarification.*

As it has been detailed in the previous point, this term is commonly employed in the field of multiphase electric drives to refer to x-y currents. These secondary currents are directly related to stator copper losses in six-phase electric drives when the machine is configured with a distributed stator winding [18]. For this reason, it is common to define their reference values with a null value.

The revised version of the manuscript clarifies that secondary currents and x-y currents are in fact synonymous.

5) *It is not clear in lines (172-175) why the weight Kxy must be selected to minimize the injection of xy current components. In this scenario, the alfa-beta current components contribute significantly to the electromagnetic torque, and the associated three phase set windings of the alfa-beta current components experience higher Joule losses. On the other hand, is the asymmetrical six-phase motor designed with two different three-phase windings with distinct copper sections?*

Please note that the physical meaning of the x-y components was described in the Section 2 as follows "whereas x-y currents only produce stator copper losses in IMs with distributed stator windings and negligible spatial harmonics".

Consequently, based on the contribution of these components to the torque/flux production, the most popular approach is the mitigation of x-y currents to achieve a suitable signal quality characterized by a low harmonic distortion.

Regarding the construction of the considered six-phase electric drive, this one has been carried out using the same winding section, as it is common in the field of multiphase systems. The term asymmetrical is employed because the two three-phase stator windings are spatially shifted 30^o, as shown in Figure 1 of the manuscript.

6) *It is not clear what the authors mean by the open-loop mode for the VV-MPC in lines (196-197).*

The implementation of the virtual vector voltage solution termed as VV-MPC is based on the application of two active switching states. The combination of these switching states provides a null average production in the secondary subspace, if their duty cycles are adequately applied, as it has been described in the previous manuscript version. Since the application of this multi-vector voltage output permits obtaining a null average voltage production of these undesired components, their regulation can be neglected in the cost-function. Since it is not necessary feedback of the x-y currents, the control of such secondary currents is termed as open-loop. This term is commonly used in literature [27].

The new manuscript version has been updated to detail in a more specific manner this fact.

7) *It is not clear why the VV-MPC provides an improvement in terms of current quality compared to FCS-MPC, as mentioned in lines (209-210).*

The origin of the improvement provided by the multi-vector solutions can be identified observing Figure 2 of the manuscript. The implementation of a conventional FCS-MPC based on the application a single switching state per control cycle cannot simultaneously satisfy an active injection α-β currents with a null production of x-y components. Therefore, the price of an active production of flux/torque is an important harmonic distortion. Fortunately, as shown in [26], the usage of active control actions with a null average production in the secondary subspace permits achieving a significant enhancement in term of harmonic mitigation.

A more detailed description has been added to the new manuscript version.

8) *Please include some high-quality references regarding the influencing factors (IF) in section 4.*

Thank you for your efforts to improve the quality of the document. Some high-quality references that support the paramount role of these factors in the performance of MPC strategies in multiphase drives has been added to the new manuscript version.

To be more specific about this issue the following list permits identified the references employed for each influencing factor:

IF1. Spatial and time harmonics: [R2.9]-[R2-10]

IF2. Secondary components: [18]- [R2.11]

IF3. Electric parameter values: [42]-[R2.12]

IF4. Dc-link usage: [R2.12]-[R2.14]

IF5. Control action nature: [23],[27]

[R2.9] V. Kindl, R. Cermak, Z. Ferkova; B. Skala, Review of Time and Space Harmonics in Multi-Phase Induction Machine. *Energies* **2020**, *13*, 496. https://doi.org/10.3390/en13020496.

[R2.10] E. Levi, R. Bojoi; F. Profumo, H. A. Toliyat and S. Williamson, “Multiphase induction motor drives – a technology status review”, *IET Electric Power Applications*, 2007, 1, (4), p. 489-516, DOI: 10.1049/iet-epa:20060342

[R2.11] A. S. Abdel-Khalik, M. S. Abdel-Majeed, and S. Ahmed, “Effect of winding configuration on six-phase induction machine parameters and performance,” *IEEE Access*, vol. 8, DOI 10.1109/ACCESS.2020.3044025, pp. 223 009–223 020, 2020.

[R2.12] J. Rodriguez et al., "Latest Advances of Model Predictive Control in Electrical Drives—Part II: Applications and Benchmarking with Classical Control Methods," *IEEE Transactions on Power Electronics*, vol. 37, no. 5, pp. 5047-5061, May 2022, doi: 10.1109/TPEL.2021.3121589.

[R2.13] H. S. Che and W. P. Hew, "Dual three-phase operation of single neutral symmetrical six-phase machine for improved performance," *IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society*, Yokohama, Japan, 2015, pp. 001176-001181, doi: 10.1109/IECON.2015.7392259.

[R2.14] A.G. Yepes, J. Doval-Gandoy, F. Baneira, and H. A. Toliyat, “Comparison of stator winding connections in multiphase drives under healthy operation and with one open converter leg,” *IET Electric Power Applications*, 14(4), 584-596.

9) *It is not clear what is being depicted in Figure 12: are these currents in the xy axes? Is it showing current ripple? Is it demonstrating the step response of the command tracking performance? Please improve the graphical presentation of the results and provide a clearer explanation of the intended illustration. Additionally, why is the same result not shown for the alpha-beta axis currents?*

Please note that the waveform of the phase currents in multiphase electric drives is particularly dependent on the secondary currents [R2.11]. For this reason, the analysis proposed in the Figure 12 is focused on these components. In fact, as it has been described in the previous manuscript version the objective of these analytical results is to show the impact of the stator parameter on the behaviour of these currents when different multi-vector solutions are implemented. In fact, Figure 12 shows the mitigation of these secondary currents for different alternative of virtual voltage vectors. On the other hand, these theoretical results have been confirmed with the experimental results of Section 5.

10) *In paragraph 4.2, what is meant by 'current tracking performance'? Does it refer to step response of the command tracking performance? Is it evaluating the bandwidth related to current control? Perhaps the term creates confusion with 'command tracking".*

Please note that in the field of speed-variable electric drives, the speed regulation is commonly provided by the regulation of different currents [18]. For this reason, the command variables are typically currents. As a consequence, it is habitual to employ the term of “current tracking” [18] to simply indicate if the measured currents are properly following their references. If the current tracking performance is good, it means that measured currents are properly following (tracking) their reference values, while the tracking performance is bad if the opposite occurs.

11) *For both paragraph 4.2 and 4.3, it would be helpful to present simulations illustrating a direct comparison in terms of current tracking performance and power losses.*

Thank so much for your suggestion. In fact, the authors agree with the importance of the mentioned analysis. For that reason, the previous manuscript version included Figure 14, 18 and 19, where the reader can find experimental results about the tracking of the different currents (PtP_{xy} and MSE_{dq}) and the losses of the system.

The provided results permit to the reader analyse the behaviour of four different control schemes in four six-phase electric drives characterized by diverse electrical stator parameter. In addition, the information provided to the reader in Tables 4 and 5 allows obtaining a qualitative analysis about the current tracking.

12) *In paragraph 5.2.1, when comparing various MPC methods in terms of current quality, it would be useful to include the PI-based solution implementing an indirect rotor field-oriented control (IRFOC).*

The reviewer is right, the comparison between IRFOC and MPC schemes has been a hot topic of the field in the last decade. In this regard, there are several works focused on a comparative analysis of these popular regulation algorithms using different perspectives [18]. This form of study is not exclusive for conventional FCS-MPC schemes where a single control action is applied per control cycle. The mentioned analysis has also been carried out when multi-vector solutions have been implemented as implicit modulation stages of MPC schemes. In fact, the authors of this manuscript published two different journal papers [23],[27] where an explicit comparison between multi-vector solutions and IRFOC scheme. Based on the provided results in [27], FCS-MPC schemes can achieve similar current quality to linear controllers using an explicit modulation stage.

Nevertheless, in this manuscript the contribution is not focused on the benefits of multi-vector solutions over IRFOC schemes. As it has been indicated in the proposed title, the objective is to guide to the control designer in the selection of the most appropriate multi-vector solution based on the employed electric drive and the control goals. For that purpose, the main influencing factors have been identified and described, as well as different electric drives have been employed to test in a more generalized manner the response of the considered multi-vector solutions. On the other hand, the global losses of the system have been estimated looking for a more complete response in terms of control performance. In spite of the previous information Figures 16 and 17 have been modified to include the phase currents when a IRFOC scheme using a CB-PWM stage is implemented.

13) *Figure 17 is placed within the wrong paragraph. The same applies to Figure 18 and Tables 4-5. The same issue is present with Figures 19 and 20.*

Thank so much for your comment and sorry for the typo. The location of the Figures 17, 18 and 19 has been solved.

14) *Include in Figures 19 and 20 the case with the PI-based solution implementing an IRFOC.*

Please see the response of point 12 where more information about the comparison between IRFOC and FCS-MPC schemes has been provided.